Chapter 10

UNIFORM STORMWATER BMP SIZING CRITERIA

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10.0. INTRODUCTION

Stormwater management policies have been developed over the years in an attempt to mitigate the impact of land development on aquatic systems and property, as discussed previously. Increased flash flooding and the associated flood damage in urbanizing areas gave rise to stormwater management policies based on controlling the peak discharge of runoff from the development site. In addition to the structural damage, significant erosion of the channel bed and banks was considered to be a detriment to the value of property. Detention basins sized to reduce the post-development peak discharge to the pre-developed rates became an acceptable and commonly used method of mitigating these impacts of urbanization. As channels eroded, more and more localities developed peak rate control policies aimed at controlling channel erosion and localized flooding. These policies, however, were still based on a peak rate of discharge and did not address the increased *volume* and *frequency* of the peak discharge. (MDE, 2000)

Both theory and experience indicates that, while detention basins designed to control peak discharge are effective in controlling peak flow rates, the basins are ineffective in controlling the degradation of erodible channels downstream of the basin. (McCuen, Moglen, 1988). Similarly, stormwater management designs must incorporate methods for improving water quality. (MDE, 2000) The traditional detention approach alone is not sufficient.

In fact, Virginia's new way to approach stormwater management involves a paradigm shift, establishing on-site ***runoff volume reduction*** as the main priority. In conjunction with that shift, the term ***Treatment Volume (Tv)*** will replace the term *Water Quality Volume* to represent the volume of runoff that must be reduced and/or treated to achieve compliance with the water quality criteria in the Virginia Stormwater Management Regulations. These concepts are integrated in Virginia's new ***Runoff Reduction Method (RRM)*** compliance calculation spreadsheet (see **Section 10.1.2** below).

This chapter presents an updated, more effective unified approach for sizing stormwater BMPs in Virginia to meet pollutant removal goals, maintain groundwater recharge, reduce channel erosion, prevent overbank flooding, and pass extreme floods. For a summary, please consult **Table 10.1** below. The remaining sections describe the applicable sizing issues and the associated criteria in detail and present guidance on how to properly compute and apply the required storage volumes.

The Virginia Stormwater Management Regulations directly address three (in boldface type) of the five different stormwater BMP sizing issues that are typically addressed in such regulations and ordinances (the three in italics and boldface type are addressed in the Virginia regulations):

- Groundwater Recharge and/or Runoff Volume Reduction
- ***Water Quality Protection***
- ***Receiving Channel Protection***
- ***Frequent/Overbank Flooding***
- Flooding from Extreme Storms

Table 10.1. Summary of the Statewide Stormwater BMP Sizing Criteria

Sizing Criteria	Description of Stormwater Sizing Criteria
Recharge Volume (Re_v) (acre-feet)	Virginia has no separate recharge requirement. The Virginia Runoff Reduction Methodology serves to address both the recharge and water quality treatment criteria in the regulations. The Method can also potentially meet or help to meet the water quantity control criteria. See Appendix 13-A for an optional approach to assuring reasonable groundwater recharge.
Treatment Volume (T_v) (acre-feet)	$Tv = \frac{P \times (Rvi \times \%i + Rvt \times \%t + Rvf \times \%f) \times SA}{12}$ Where: Tv = Runoff reduction volume in acre feet P = Depth of rainfall (1-inch) for “water quality” event Rvi = runoff coefficient for impervious cover[1] Rvt = runoff coefficient for turf cover or disturbed soils[1] Rvf = runoff coefficient for forest cover[1] %i = percent of site in impervious cover %t = percent of site in turf cover %f = percent of site in forest cover SA = total site area, in acres [1] Obtain Rv values from **Table 10.3** below
Channel Protection Storage Volume (Cp_v)	The required storage volume is situational, based on the type of receiving channel that exists downstream of the drainage outfall (4 VAC 50-60-66 A), with the flow released at a rate that will prevent erosion of the receiving channel; depending upon how much runoff volume reduction is achieved on-site with water quality BMPs, there may be little or no additional Cp_v; detention upstream of natural receiving channels is based on situational energy balance formulas described on page 13 of this chapter and based on the 1-year 24-hour storm.
Overbank Flood Protection Volume (Q_{10})	The required storage volume is situational, based on the type of receiving channel that exists downstream of the drainage outfall (4 VAC 50-60-66 B), with the flow released at a rate that will prevent erosion of the receiving channel; depending upon how much runoff volume reduction is achieved on-site with water quality BMPs, there may be little or no additional Q_{10}; detention upstream of natural receiving channels is based on the energy balance formula described on page 13 of this chapter and based on the 10-year 24-hour storm.
Extreme Flood Protection Volume (Q_f)	Consult the appropriate review authority. Normally, no control is required if development is excluded from the 100-year floodplain and downstream conveyance is adequate for up to the 10-year 24-hour design storm.

The general goal of each of these stormwater management criteria is to ensure that stormwater runoff at development sites is managed in such a way that the post-development hydrology and runoff characteristics at the development site closely resemble the pre-development hydrology and runoff characteristics over a wide range of rainfall events. Different BMP sizing criteria apply for each of these elements of stormwater management.

10.1. UNIFIED SIZING CRITERIA

A unified approach is the most effective way to develop and present stormwater BMP sizing criteria. The goal of a unified sizing framework is to develop a consistent approach for sizing BMPs that can:

- ***Avoid-Minimize-Mitigate.*** The first (nested) goals of on-site stormwater management should be (1) avoiding runoff impacts whenever possible, (2) minimizing them when complete avoidance is not possible, and (3) mitigating the impacts (runoff reduction, detention/retention and treatment BMPs) when sufficient minimization of impacts is not achievable. Using *Environmental Site Design* techniques is very effective in avoiding and minimizing runoff impacts.

- ***Promote Environmental Design and On-Site Runoff Reduction.*** Be structured in a manner so that property owners have real incentives to reduce storage volumes (and costs) by applying environmental site design (ESD) techniques and using runoff reduction practices.

- ***Perform Effectively.*** Manage enough stormwater runoff volume to actually solve the stormwater problems that the stormwater management regulations are supposed to address (to avoid, minimize or mitigate the potential harmful impacts to downstream waters and properties).

- ***Perform Efficiently.*** Manage just enough runoff volume to address the problems but not over-control them. Providing more stormwater storage is not always better and can greatly increase construction costs and consume valuable land.

- ***Be Simple to Administer.*** Be understandable, relatively easy to calculate with current hydrologic models, and workable over a range of development conditions and intensities. In addition, stormwater management criteria should be clear and straightforward, and backed up by the regulations and law, to avoid needless disputes between design engineers and plan reviewers when they are applied to development sites.

- ***Be Flexible to Respond to Special Site Conditions.*** Define certain site conditions or development scenarios where individual stormwater sizing criteria may be relaxed or waived when they are clearly inappropriate or infeasible. (CWP)

A unified framework for sizing stormwater BMPs provides greater consistency and integration among the different stormwater management criteria outlined in the regulations. It also establishes a foundation for stormwater management that can be used to address all of the stormwater problems associated with the entire spectrum of rainfall events, provided that the regulations adequately address the stormwater management sizing issues listed above. Over the course of a year, many precipitation events occur within a community. Most events are quite small, but a few can create several inches of rainfall. The range of storms that typically occur can be represented in a rainfall frequency spectrum analysis (RFSA), describing how often, on average, various precipitation events (adjusted for snowfall) occur during a normal year.

To understand the link between the RFSA and the various stormwater management criteria, it is important to understand that each of the criteria is aimed at controlling the stormwater runoff from a specific rainfall event. The rainfall events that are the target of the various stormwater management criteria are described in more detail as follows:

- ***Groundwater Recharge and/or Runoff Volume Reduction.*** Targets the rainfall events that create little or no stormwater runoff, but that produces much of the annual groundwater recharge that occurs at the development site.

- ***Water Quality Protection.*** Targets the rainfall events that transport the majority of stormwater pollutants off the development site.

- ***Receiving Channel Protection.*** Targets the channel-forming storm events that generate bankfull and sub-bankfull flows in downstream channels and cause downstream erosion of the channel bed and banks.

- ***Frequent/Overbank Flooding.*** Targets the large and relatively infrequent storm events that cause streams to leave their banks and spill over into the floodplain, causing damage to infrastructure and streamside property.

- ***Flooding from Extreme Storms.*** Targets the largest, most infrequent storm events that cause catastrophic flooding and threaten floodplain structures and public safety (e.g., the 100-year flood). (CWP)

An example of a typical RFSA is provided in Figure 10.1, showing the approximate ranges for storms comprising the unified sizing criteria. The figure shows the percentage of rainfall events that are equal to or less than an indicated rainfall depth. As can be seen, the majority of storm events are relatively small, but there is a sharp upward inflection point that occurs just above one-inch of rainfall (90th percentile rainfall event). (CWP)

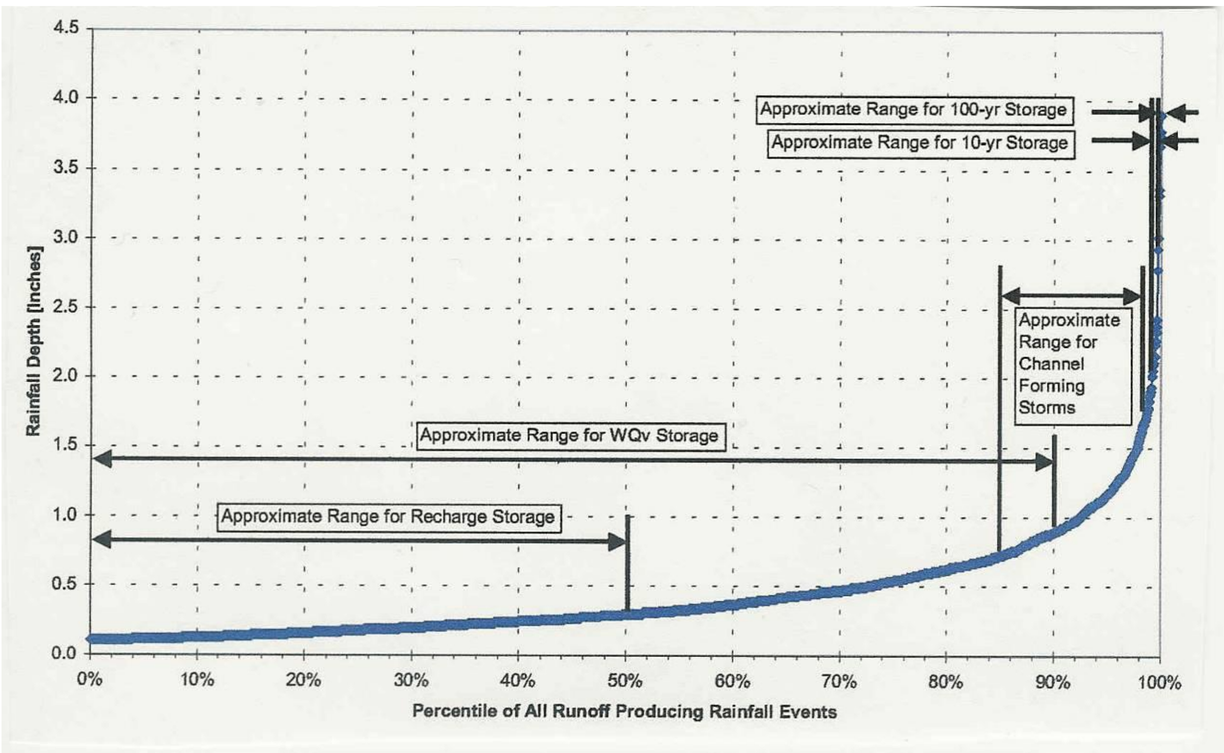

Figure 10.1. Approximate Ranges for Storms Comprising the Unified Sizing Criteria

As one might guess, the management of larger and more infrequent rainfall events (i.e., overbank flooding and extreme flooding) requires larger stormwater BMPs with larger storage volumes. For example, the storage volume required to manage runoff from the extreme flood storm event is significantly larger than that required to manage the runoff from the channel protection storm event. Likewise, the storage volume required to manage the runoff from the channel protection storm event is larger than that required to manage runoff from the water quality protection storm event.

The relationship between the five stormwater sizing criteria is best understood visually as a layer cake, with the recharge/volume control element being the thinnest layer at the bottom and the extreme storm control comprising the thickest layer at the top. As well, the volume involved in the lower/smaller storms is part of the volume for the next larger storm. That is, the runoff volume associated with groundwater recharge is nested in and part of the volume associated with the need for water quality treatment, which is nested in and part of the volume associated with stream channel protection, etc. Therefore, when a designer applies BMPs to address the treatment volume, he is also addressing at least part of the channel protection volume, etc. **Figure 10.2** illustrates the relationship between the five types of stormwater sizing criteria.

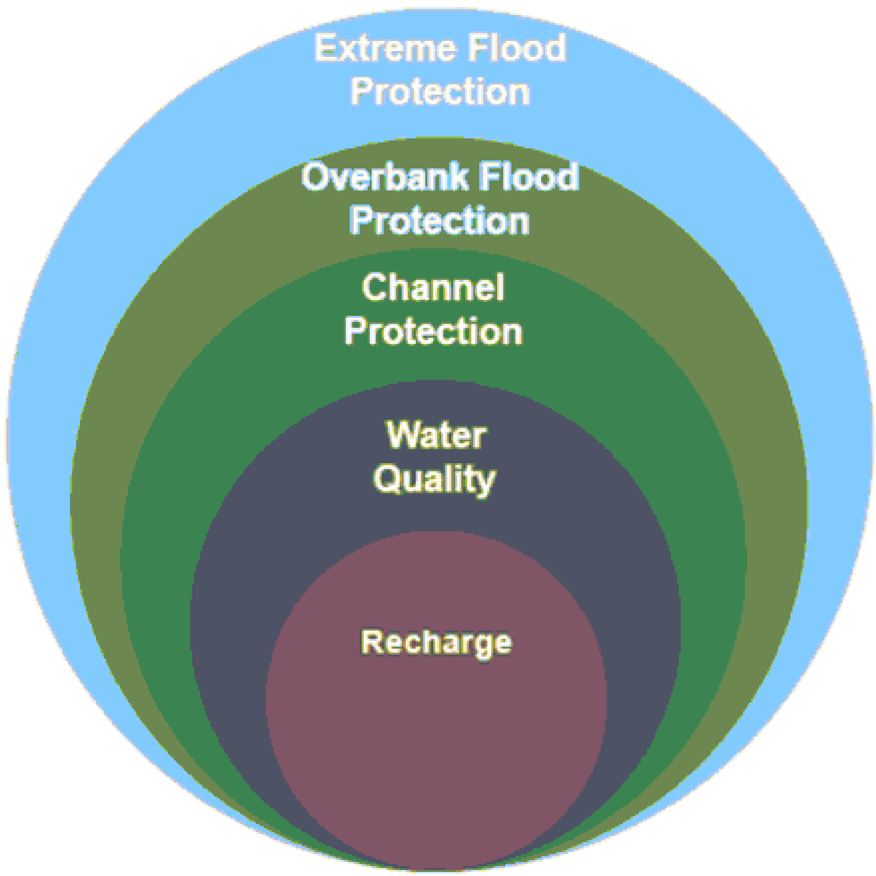

Figure 10.2. Graphic Representation of the Unified Stormwater BMP Sizing Criteria (Source: CWP)

The following sections provide a discussion of various sizing criteria for stormwater volume reduction, stormwater quality control, stream channel protection, and flood control BMPs in Virginia.

10.1.1. Runoff Volume Reduction

The intent of Virginia's Runoff Reduction Method is to (1) reduce the total volume of runoff carrying pollutants, (2) decrease the amount of runoff to receiving streams, and (3) maintain groundwater recharge rates at development sites sufficient to preserve existing water table elevations and support natural base flows in streams and wetlands. Under natural conditions, the amount of recharge that occurs at a site is a function of slope, soil type, vegetative cover, precipitation and evapotranspiration. Sites with natural ground cover, such as forest and meadow, typically exhibit higher recharge rates, lower runoff volumes and greater transpiration losses than sites dominated by impervious cover. Since land development increases impervious cover, a net decrease in recharge rates is inevitable.

Virginia's new water quality protection criteria will, in fact, reduce runoff volume and, in the process, accomplish a significant amount of groundwater recharge using the same BMPs. In that light, separate volume reduction/groundwater recharge criteria may not be necessary..

It is important to note that under Virginia's stormwater management act and regulations, local governments have the option to adopt more stringent criteria than those specified in the act and state regulations, subject to certain conditions *(see the section about this at the end of this chapter)*. DCR is aware that some localities may be interested in including specific groundwater recharge requirements in their local ordinances. One reason for this is that some communities are concerned that stormwater plan designers dealing with less complex sites may avoid implementing runoff volume reduction practices in lieu of simply specifying a large pond practice that may be able to otherwise comply with the various regulatory requirements. While this is a legally acceptable alternative, it would not address the need to recharge local groundwater in order to maintain stream base flow during periods of dry weather.

In view of that possibility, DCR staff has reviewed approaches to setting groundwater recharge criteria that have been used in other states with land and weather conditions similar to those we have in Virginia. For those localities desiring to adopt a groundwater recharge requirement, DCR believes the approach set forth in **Appendix 10-A** (at the end of this chapter) makes the most sense for application in Virginia.

10.1.2. Water Quality Treatment

Treatment of stormwater runoff is needed to meet established water quality standards and to protect aquatic life, designated stream uses and sensitive water resources. A significant number of water quality monitoring studies has revealed that untreated stormwater runoff contains high concentrations of sediments, nutrients, bacteria, metals, oxygen-demanding substances, hydrocarbons and other pollutants (Pitt et al., 2005), which have a significant impact on stream and lake quality (CWP, 2001 and CWP, 2003).

The Virginia Stormwater Management Regulations previously required that the *first flush* of runoff be captured and "treated" to remove pollutants. The first flush, or *water quality volume* (WQ_v), is defined in the Act and regulations as the first ½-inch of runoff from impervious surfaces. However, scientists now have reason to question whether the first flush is a consistent phenomenon and believe that this initial volume of runoff does not capture the full range of pollutants with which we are concerned in urban/suburban runoff. Therefore, many stormwater management regulatory authorities have migrated away from regulating the first flush and toward using the RFSA methodology to select a design storm that statistically allows them to treat the majority of rain that falls each year at a reasonable cost.

While the first flush from a storm event is considered to contain the highest concentration of pollutants, there is considerable debate over the intensity of rain needed to wash the pollutants from the urban landscape (CWP). Studies have shown that intensity is the critical wash off factor for most storm events, and many people can intuitively comprehend that higher intensity rains leave impervious surfaces cleaner than lower intensity rains. (Adams, 1997). The typical NRCS rainfall hyetograph starts with a low rainfall intensity which gradually rises to a peak and then declines. This may indicate that in some cases the designated Treatment Volume provided in a stormwater basin may fill up with the relatively clean water at the onset of a rain event, consequently allowing the larger flows associated with the high intensity rain and pollutant wash-off to pass through the facility.

A similar discussion on the design criteria for water quality structures focuses on the "volume" of runoff versus the "rate", or even the return frequency, of runoff. The water quality volume or first flush is detained in a basin or impoundment structure to allow the pollutants to settle out. Whether that specific volume of runoff enters the basin gradually, or as the result of a sudden high intensity rain, it is still detained for a period of time. Filtering structures, on the other hand, can handle only a certain design flow rate. Sudden high intensity rain will typically generate too much runoff too fast and therefore bypass the treatment facility. ***Therefore, many stormwater management experts are now reluctant to rely on treating the first flush alone, and more effective methods have been developed to determine the volume of runoff that needs to be treated***. Furthermore, the USEPA and others now focus more on the total load captured, rather than aiming at particular concentrations of pollutants.

DCR had the CWP conduct rainfall frequency analyses for five different locations in Virginia, to see if there were significant variations in the 90^{th} percentile rainfall depth (see **Figure 10.3** below):

- Abingdon 0.97 inch
- Near Harrisonburg 1.05 inches
- Lynchburg 1.23 inches
- Richmond 1.29 inches
- Northern Virginia 1.14 inches

The rationale for using the 90^{th} percentile event is that it represents the majority of runoff volume on an annual basis, and that larger events would be very difficult and costly to control for the same level of water quality protection (as indicated by the upward inflection of the curve at the 90% mark). However, these larger storm events would still receive partial treatment for water quality, as well as storage for channel protection and flood control. To distinguish this volume from the term *water quality volume*, which is defined in the Act and regulations, we will call this the "Treatment Volume" (T_v).

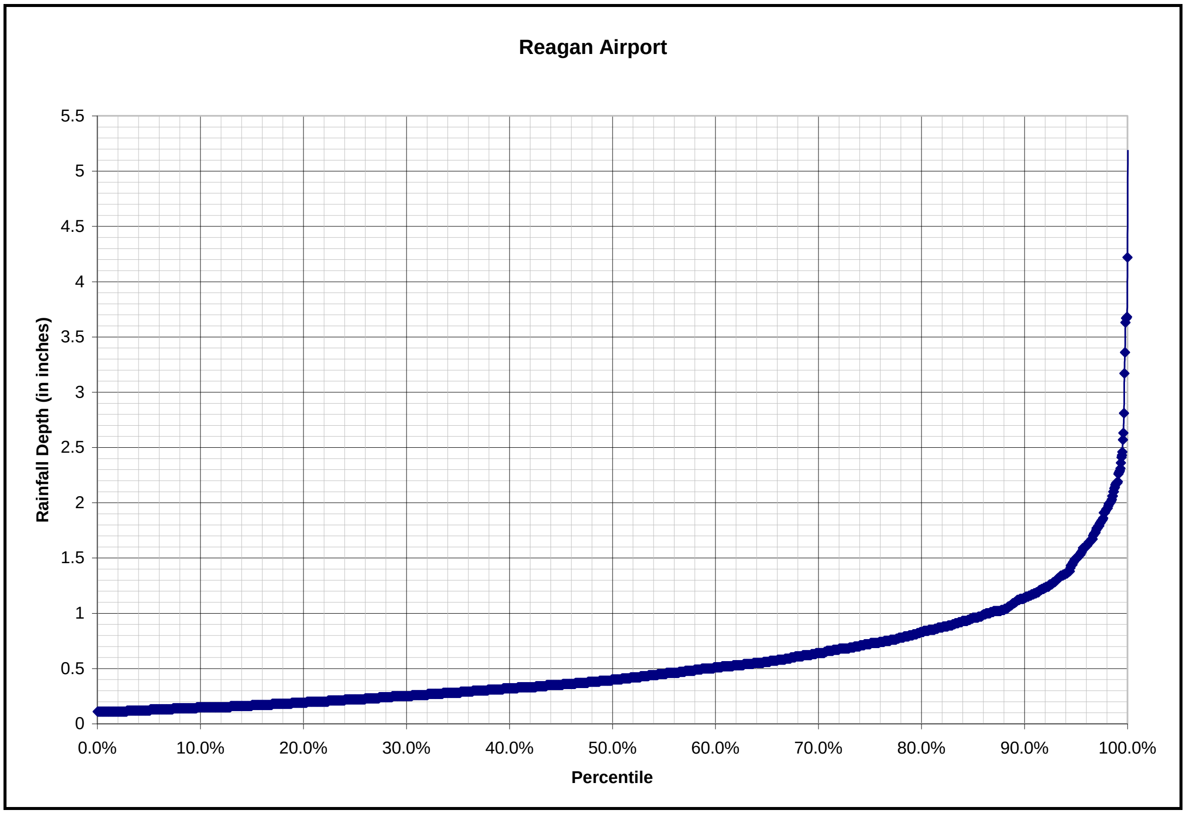

Figure 10.3. Rainfall Frequency Curve for Reagan Int'l Airport (DeBlander, et al., 2008).

For simplicity and consistency, it is reasonable use a single rainfall amount for the purpose of establishing a statewide standard. Based on this analysis and the use of the 1-inch rainfall event for water quality protection purposes in other Bay-region states, DCR established the 1-inch rainfall event as the standard for the water quality treatment.

Treatment Volume is the central component of the Virginia Runoff Reduction method. By applying site design and both structural and nonstructural practices, the designer can reduce the treatment volume by reducing the overall volume of runoff leaving a site. In this regard, the T_v is the main "currency" for site compliance.

In the Virginia Runoff Reduction Method, a site's T_v is calculated by multiplying the "water quality" rainfall depth (one-inch) and a composite of three site cover runoff coefficients (forest, disturbed soils, and impervious cover) present at the site, as shown in **Equation 10.1** below (CWP et al., 2008). This method generates a T_v of close to 1 inch for highly impervious sites and gradually decreasing volumes for gradually decreasing levels of imperviousness.

Equation 10.1. Runoff Reduction Method to Determine the Stormwater Treatment Volume (Tv)

$$Tv = \frac{P \times (Rvi \times \%i + Rvt \times \%t + Rvf \times \%f) \times SA}{12}$$

Where:

Tv = Runoff reduction Treatment [a.s.] volume in acre feet
P = Depth of rainfall (1-inch) for "water quality" event
Rvi = runoff coefficient for impervious cover [1]
Rvt = runoff coefficient for turf cover or disturbed soils [1]
Rvf = runoff coefficient for forest cover1
%i = percent of site in impervious cover (fraction) [a.s.]
%t = percent of site in turf cover (fraction) [a.s.]
%f = percent of site in forest cover (fraction) [a.s.]
SA = total site area, in acres

[1] Obtain Rv values from **Table 10.2** below

The proposed Treatment Volume has several distinct advantages when it comes to evaluating runoff reduction practices and sizing BMPs:

- The T_v provides effective stormwater treatment for approximately 90% of the annual runoff volume from the site, and larger storms will be partially treated.
- Storage is a direct function of impervious cover and disturbed soils, which provides designers incentives to minimize the area of both at a site.
- The 90% storm event approach to defining the Treatment Volume is widely accepted and is consistent with other state stormwater manuals (MDE, 2000, ARC, 2002, NYDEC, 2001, VTDEC, 2002, OME, 2003, MPCA, 2005).
- The T_v approach provides adequate storage to treat pollutants for a range of storm events. This is important since the first flush effect has been found to be modest for many pollutants (Pitt et al 2005).
- T_v provides an objective measure to gage the aggregate performance of environmental site design, runoff reduction and other innovative practices, and conventional BMPs together using a common currency (runoff volume).
- Calculating the T_v explicitly acknowledges the difference between forest and turf cover and disturbed and undisturbed soils. This creates incentives to conserve forests and reduce mass grading and provides a defensible basis for computing runoff reduction volumes for these actions.

10.1.2.1. Runoff Coefficients – Moving Beyond Impervious Cover Alone

The negative impacts of increased impervious cover (IC) on receiving water bodies have been well documented (CWP 2003, Walsh et al. 2004; Shuster et al. 2005; Bilkovic et al. 2006). Due to wide-spread acceptance of this relationship, IC has frequently been used in watershed and site design efforts as a chief indicator of stormwater impacts.

More recent research, however, indicates that other land covers, such as disturbed soils and managed turf, also impact stormwater quality (Law et al, 2008). Numerous studies have documented the impact of grading and construction on the compaction of soils, as measured by increase in bulk density, declines in soil permeability, and increases in the runoff coefficient (OCSCD et al, 2001; Pitt et al, 2002; Schueler and Holland, 2000). These areas of compacted pervious cover (lawn or turf) have a much greater hydrologic response to rainfall than forest or pasture.

Further, highly managed turf can contribute to elevated nutrient loads. Typical turf management activities include mowing, active recreational use, and fertilizer and pesticide applications (Robbins and Birkenholtz 2003). An analysis of Virginia-specific data from the National Stormwater Quality Database (Pitt et al. 2004) found that runoff from monitoring sites with relatively low IC residential land uses contained significantly higher nutrient concentrations than sites with higher IC non-residential uses (CWP & VA DCR, 2007). This suggests that residential areas with relatively low IC can have disturbed and intensively managed pervious areas that contribute to elevated nutrient levels.

The failure to account for the altered characteristics of disturbed urban soils and managed turf can result in an underestimation of stormwater runoff and pollutant loads generated from urban pervious areas. Therefore, the computation and compliance system for nutrients should take into account impervious cover as well as other land uses.

The runoff coefficients provided in **Table 10.2** (CWP et al., 2008) were derived from research by Pitt et al (2005), Lichter and Lindsey (1994), Schueler (2001a), Schueler, (2001b), Legg et al (1996), Pitt et al (1999), Schueler (1987) and Cappiella et al (2005). As shown in this table, the effect of grading, site disturbance, and soil compaction greatly increases the runoff coefficient compared to forested areas. It is important to understand that these coefficients were developed for use with the Virginia Runoff Reduction Method. However, they should not be used with other standard methodologies (e.g., NRCS, Modified Rational, etc.) to compute peak flows and perform detention routings in ponds. The other methodologies have their own set criteria.

Table 10.2. Site Cover Runoff Coefficients (Rv)

Soil Cover Condition	Runoff Coefficients			
	HSG-A	HSG-B	HSG-C	HSG-D
Forest	0.02	0.03	0.04	0.05
Disturbed Soil or Managed Turf	0.15	0.20	0.22	0.25
Impervious Cover	0.95			

The advantage of a computation system for nutrients that takes into account a range of land covers is that stormwater management designs will have a higher likelihood of treating *all* relevant land uses that contribute nutrients to waterways. In addition, such a system provides incentives to incorporate environmental site design techniques, such as maintaining or restoring forest cover, as a means of reducing site compliance requirements.

10.1.3. Receiving Stream Channel Protection

The purpose of channel protection criteria is to prevent habitat degradation and erosion in natural streams caused by an increased frequency of bankfull and sub-bankfull stormwater flows. Channel protection criteria seek to minimize downstream channel enlargement and incision that is a common consequence of development (CWP, 2004a). As fields and forests are converted to impervious surfaces, the volume and frequency of runoff is increased significantly. Research indicates that urbanization causes channels to expand to two-to-ten times their original size in order to accommodate the increased volume and frequency of runoff caused by increased impervious cover, as well as the increased conveyance efficiency of curbs, gutters and storm drains (for a review, see CWP, 2003 and 2005a).

Such stream channel enlargement significantly impacts stream habitat, water quality and public infrastructure. Streambank erosion sharply increases total annual sediment yield and nutrient loads, as nutrient-rich floodplain soils are eroded and transported downstream. In addition, channel erosion degrades and simplifies stream habitat structure, diminishing aquatic biodiversity. Lastly, channel erosion can cause severe damage to bridge, culvert and sewer infrastructure and loss of private property.

Stream channel erosion results primarily from high scour velocities over extended durations of time. Historically, peak discharge control for the 2-year storm has been applied to control channel erosion in Virginia, as it has been in most states. Many communities continue to use that criterion today. This requirement seeks to keep the post-development peak discharge rate for the 2-year 24-hour design storm at the pre-development rate. The reasoning behind this criterion is that the bankfull discharge for most streams has a storm recurrence interval of between one and two years, with approximately 1.5 years as the most prevalent (Leopold, 1964 and 1994). The expectation has been that maintaining this discharge rate should prevent downstream erosion.

Recent research, however, indicates that 2-year peak discharge control does not protect channels from downstream erosion and may actually contribute to erosion, since banks are exposed to a longer duration of erosive bankfull and sub-bankfull events (MacRae, 1993, MacRae, 1996, McCuen and Moglen, 1988). Thus, while 2-year peak discharge control may have some value for overbank flood control, it is not effective as a channel protection criterion, since it may actually extend the duration of erosive velocities in the stream and increase downstream channel erosion. This is explained further in **Appendix B** of this chapter.

The Virginia Stormwater Management Regulations now address prevention of stream channel erosion with new criteria superseding those of Minimum Standard 19 of the Virginia Erosion and Sediment Control Regulations (4 VAC 50-30-40.19), which was the previous standard. This criteria requires that *"Properties, state waters, and stormwater conveyances within or* *downstream of a land disturbing activity shall be protected from sediment deposition, erosion and flood damage due to unmanaged quantity of stormwater and changes in runoff characteristics. . . .”* (4 VAC 50-60-66). The term *runoff characteristics* is defined in the regulations as follows: *“Runoff characteristics include, but are not limited to velocity, peak flow rate, volume, time of concentration, and flow duration, and their influence on channel morphology including sinuosity, channel cross-sectional area, and channel slope.”*

For channel protection sizing purposes, Virginia has now adopted the most widely recommended channel protection criteria of the last few years – that is, to provide 24 hours of extended detention for the runoff generated from the post-development 1-year 24-hour design storm. This runoff volume is stored and gradually released at a rate that prevents critical erosive velocities from occurring in downstream channels over the entire storm hydrograph. In addition, *man-made channels* are analyzed for adequacy to convey the 10-year peak discharge within the channel banks and the 2-year peak discharge at a non-erosive velocity. These criteria, used in Maryland, New York, Vermont, Georgia, and other states result in significantly lowered discharge rates and velocities considered to be non-erosive, despite the longer impact time and increased frequency. It is relatively easy to compute at most development sites using available hydrologic and hydraulic models. It is important to note that the control volume calculated for channel protection purposes *includes* the control volume calculated for water quality protection purposes.

However, some stormwater experts have begun to question whether addressing the peak flow rate alone, without considering changes in runoff volume, is sufficient to adequately protect channels from erosion. These experts contend that the channel is formed naturally based on the “energy” represented in flows through the system. That energy is not just a result of the peak discharge, but also a reflection of the velocity and volume of flow.

Therefore, Virginia has modified the channel protection sizing criteria in order to compensate for the increase in runoff volume as well. By addressing peak discharge and volume together, DCR presumes the velocity will be adequately managed as well.

To accomplish this, the regulations incorporate two versions of a method set out in § 10.1-603.4.7.(iii) of the Stormwater Management Law, as reflected in an equation developed by Fairfax County. Using this equation, the post-development peak flow rates of runoff from 1-year 24-hour storm at the development site are reduced to below the respective peak rates of runoff for the site based on (1) the pre-development land cover, if discharging to a natural stream channel that is in stable condition, or (2) good forested condition (e.g., for NRCS method, a cover type of “woods” and a hydrologic condition of “good”), if discharging to a natural stream channel that already has excessive erosion. Both of these formulas take runoff volume into account. These reductions result in a proportional improvement and are computed as follows:

Equation 10.2. Energy Balance Equation

$$Q_{Developed} \leq I.F. \; x \; (Q_{Pre\text{-}Developed} \; x \; RV_{Pre\text{-}Developed}) \, / \, RV_{Developed}$$

Where:

$Q_{Developed}$ = The allowable peak flow rate of runoff from the developed site
$I.F.$ = Improvement factor, equal to 0.8 for sites > 1 acre or 0.9 for sites ≤ 1 acre
$Q_{Pre\text{-}Developed}$ = The peak flow rate of runoff from the site in the pre-developed condition
$RV_{Pre\text{-}Developed}$ = The volume of runoff from the site in the pre-developed condition
$RV_{Developed}$ = The volume of runoff from the site in the developed site

This method results in post-development discharges that are low enough to avoid causing channel erosion. Furthermore, the latter equation satisfies a requirement in the Stormwater Management Act (§ 10.1-603.4.7) to "*. . . improve upon the contributing share of the existing predevelopment runoff characteristics and site hydrology if stream channel erosion or localized flooding is an existing predevelopment condition*." The regulations also provide alternate methods of compliance, including using another methodology that achieves equivalent results, providing receiving channel improvements that demonstrate accommodation of post-development flows, and several exemptions from the criteria.

10.1.4. Frequent Overbank Flood Protection

The goal of this criterion is to prevent flood damage to the conveyance system and drainage infrastructure and reduce minor flooding caused by over-bank floods. Over-bank floods are defined as floods which exceed the bankfull capacity of the channel and spill over onto the floodplain, where they can damage property and structures. The key management objective is to protect downstream structures, culverts and bridges from increased over-bank flooding.

The storage needed for over-bank and extreme flood control is significantly greater than that needed for recharge and water quality together. To avoid costly and needless over-control of large storm events or the application of flood control criteria to every site, regardless of downstream or discharge conditions, the regulations include various flood control exemptions applicable to sites where there are negligible threats to downstream property or infrastructure.

Virginia has established an over-bank flood control design storm that is the same as that used to design open channels, culverts, bridges, and storm drain systems. Depending on the type and condition of the receiving stream, the regulations require post-development peak discharges from the 10-year/ 24-hour design storm event be either contained within the receiving system or controlled to reduce the pre-development peak discharge to mimic a discharge from the site if it were completely forested (4 VAC 50-60-66 B). Modeling has shown that control of the 10-year storm coupled with control of the 100-year storm effectively attenuates storm frequencies between these two events (e.g., the 25-year and 50-year design storms). Even without attenuation of the 100-year event, providing control of the 10-year storm event provides significant control of the 25-year storm event (approximately 70 to 80%).

10.1.5. Extreme Flood Protection

The goals of extreme flood protection criteria are to maintain the boundaries of the predevelopment 100-year floodplain, reduce risk to life and property from infrequent but very large floods, and protect the physical integrity of stormwater BMPs and downstream infrastructure. Control of the 10-year frequency design storm to the pre-developed rate should not be confused with out-of-bank flooding as it pertains to the 100-year floodplain mapped by the Federal Emergency Management Agency (FEMA) for watersheds with areas of greater than one square mile. The mapped 100-year floodplain is important because it is used to designate and implement the National Flood Insurance Program. Most localities in Virginia have a Floodplain Management Ordinance which controls development within the 100-year floodplain.

Protection from extreme flood damage is accomplished in one of two ways:

1. Detention storage would be required to attenuate the post-development 100-year 24-hour peak flow rate (Q_f) to the pre-development rate. This is the most stringent and expensive level of flood control. DCR does not require that BMPs be sized to hold back the 100-year storm, because this is generally not needed if the downstream development is located out of the 100-year floodplain (option 2 below). However stormwater control practices must be designed to safely bypass flows larger than the 10-year storm. For example, emergency spillways of ponds must be able to safely bypass the 100-year 24-hour storm in order to protect the structural integrity of the dams and risers. In many cases, the conveyance system leading to a stormwater structure is designed based on the discharge rate for the 10-year storm. In these situations, the conveyance systems may be the limiting hydrologic control.

2. The 100-year floodplain is reserved from development. Where this is done, control of the 100-year storm may still be required by the plan review authority if:

    a. Buildings or development are located within the ultimate 100-year floodplain; or
    b. The review authority does not completely control the 100-year floodplain.

This would necessitate floodplain boundary determinations for sites draining to small watersheds of less than one square mile in area, which would increase engineering/development costs. The most common condition under which the extreme flood control requirement is waived is when the community has a buffer or floodplain ordinance that effectively excludes development from the 100-year floodplain. However, to obtain this exemption, designers may also need to demonstrate that no downstream structures exist within the 100-year floodplain and that bridges and other infrastructure can safely pass the storm using an acceptable downstream analysis. This approach accomplishes the goal of extreme flood control by protecting the ultimate downstream 100-year floodplain rather than providing expensive upstream storage.

Hydraulic/hydrologic investigations may be required to demonstrate that downstream infrastructure is adequately protected from the 100-year storm. These investigations typically extend to the first downstream tributary of equal or greater drainage area or to any downstream dam, highway, or natural point of restricted stream flow.

To determine whether extreme flood protection controls apply:

(1) Consult with the appropriate review authority to determine the analyses required for the 100-year storm.

(2) The same hydrologic and hydraulic methods used for overbank flood control must be used to analyze the 100-year storm.

(3) In addition, off-site areas should be modeled as "ultimate condition" when the 100-year design storm event is analyzed.

10.2. MORE STRINGENT CRITERIA

Local programs are authorized under the Virginia Stormwater Management Act to require more stringent technical criteria than the state minimum criteria found in the regulations (4 VAC 50-60-63 and 65 et seq.). The more stringent criteria must be based on a watershed plan or study which justifies the criteria, and must be passed into local ordinance through the local ordinance adoption process. The scope of an acceptable watershed plan or study is somewhat subjective and, at a minimum, must stand up to the scrutiny of the local adoption process.

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Appendix 10-A

Optional Recharge Volume Approach

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FIGURES

EQUATIONS

10-A.0. INTRODUCTION

The most widely applied recharge and/or volume reduction sizing criterion is the recharge volume approach. The objective of the criteria is to mimic the average annual recharge rate for the prevailing hydrologic soil group(s) present at a development site. Therefore, the recharge volume is calculated as a function of annual pre-development recharge for a given soil group, average annual rainfall volume, and the amount of impervious cover at a site. The recharge volume is considered to be part of the total water quality volume provided at a development site and, therefore, does not require additional stormwater BMPs when water quality treatment is also required ***(see below)***. Additionally, recharge can be achieved by a range of BMP types, including infiltration, bioretention, filtration, impervious disconnection, open space preservation, or some combination of these. Note, however, that the infiltration of polluted stormwater runoff is not always desirable or even possible at some development sites. Therefore, most communities qualify their recharge and/or infiltration requirements to reflect special site conditions, protect groundwater quality, and avoid common nuisance issues. For example, the local review authority may require:

- The pretreatment of stormwater runoff prior to infiltration in some land use categories, pollution source areas (e.g. parking lots, roadways), or geological zones (e.g., karst areas).
- That recharge be restricted or prohibited at specific industrial, commercial and transport-related operations designated as potential stormwater hotspots.
- That recharge be prohibited or otherwise restricted within the vicinity of wellhead protection areas, individual wells, structures, basins.
- That recharge be restricted or prohibited within certain geological zones, such areas adjacent to unstable or fill slopes.
- That recharge requirements may be reduced or waived for minor redevelopment projects.

10-A.1 HORSELY METHOD FOR DETERMINING RECHARGE VOLUMES

One suggested approach to determining recharge volumes is based on work done by Horsley (1996) and is currently implemented in states such as Maryland, Massachusetts, and Vermont. The design approach involves determining the average annual recharge rate based on the prevailing hydrologic soil group (HSG) present at the site from the USDA-Natural Resource Conservation Service (NRCS) Soil Surveys.

HSG is an NRCS designation given to different soil types to reflect their relative surface permeability and infiltrative capability. Group A soils have low runoff potential and high infiltration rates, even when thoroughly wetted. They consist chiefly of deep, well-drained to excessively-drained sands or gravels with high infiltration rates greater than 0.3 in/hr. Group A soils include sand, loamy sand, or sandy loam. Group B soils have moderate infiltration rates (0.15 - 0.30 in/hr) and consist chiefly of soils with fine to coarse textures, such as silt loam or loam. Group C soils have low infiltration rates (0.05 - 0.15 in/hr) and fine textures. They typically have a dense layer near the surface that impedes the downward movement of water. Group C soils include sandy clay loam. Group D soils have high runoff potential with very low infiltration rates (0.0 - 0.05 in/hr). These soils consist primarily of clay soils with high swelling potential, soils with permanently high water tables, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious parent material. D soils include clay loam, silty clay loam, sandy clay, silty clay, or clay (*TR-55*, 1986).

Horsley recommended the following pre-development recharge volumes to be assigned based on NRCS soil types for humid climates receiving approximately 44 inches of annual average precipitation.

Hydrologic Soil Group Annual Recharge

A – 18 inches/year
B – 12 inches/year
C – 6 inches/year
D – 3 inches/year

Average annual rainfall varies in Virginia from approximately 34 inches per year in Rockingham and Shenandoah Counties to 48 inches in the Hampton Roads region. The State Climatology Office at the University of Virginia has determined that Virginia's overall average annual rainfall amount is 42.7 inches, based on rainfall records from 1895-1998. Therefore, the Horsley recommendation is appropriate for application in Virginia.

The objective of the criterion is to mimic the average annual recharge rate for the prevailing hydrologic soil group(s) present at the development site. Therefore, the recharge volume can be determined as a function of annual pre-development recharge for a given soil group, average annual rainfall volume, and amount of impervious cover at a site. Being a function of site impervious cover, the criterion provides incentive to planners and developers to reduce site imperviousness. Based on this approach, Maryland, our closest state neighbor using this approach (based on an average annual rainfall there of 42 inches) developed the following recharge criteria:

Equation 10-A.1. Site Recharge Volume Requirement
(the percent volume method)

$$Re_v = [(S)(R_v)(A)] / 12$$

OR

Equation 10-A.2. Modified Site Recharge Volume Requirement
(the percent area method)

$$Re_v = (S)(Ai)$$

Where

R_v = 0.05 + 0.009 (I), where I is the percent of impervious cover
A = the site area, in acres
Ai = the measured impervious cover
S = the soil-specific recharge factors, as follows:

HSG-A – 0.38 inches x impervious area
HSG-B – 0.26 inches x impervious area
HSG-C – 0.13 inches x impervious area
HSG-D – 0.07 inches x impervious area

The relationship between the Re_v and site imperviousness is shown in graphical form in **Figure 10-A.1**. The practical implication is that a fairly modest volume of infiltration is needed to maintain recharge rates for B, C and D soils, even if the site is highly impervious. The recharge volume is considered to be part of the total Treatment Volume (T_v) that must be provided at a site and can be achieved by various stormwater BMPs, either individually or in combination.

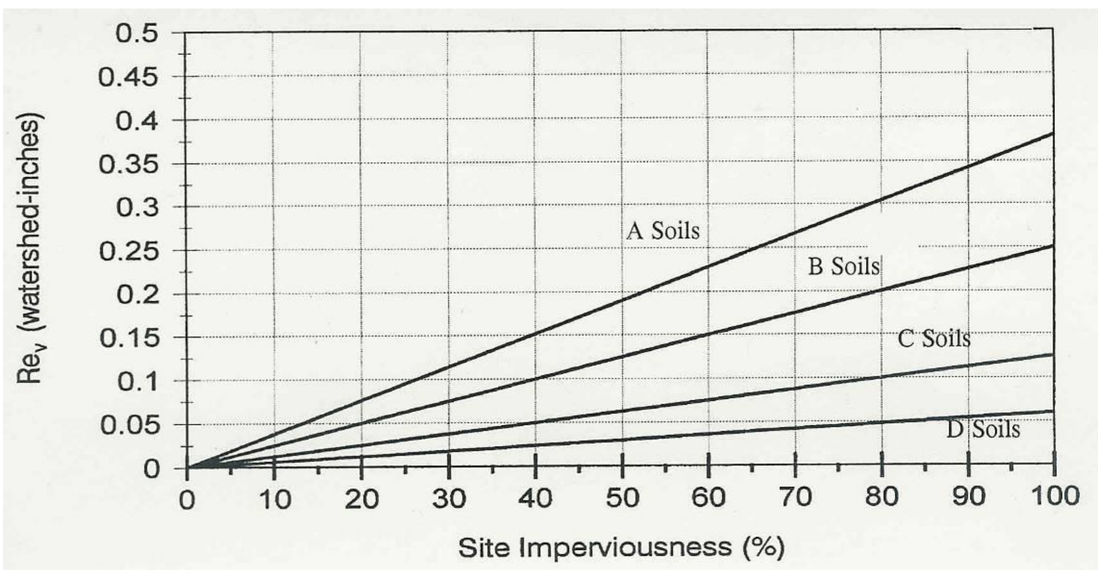

Figure 10-A.1. Relationship between Re_v and Site Impervious Cover

Drainage areas having no impervious cover and no proposed land disturbance during development may be excluded from the Re_v calculations. Designers are encouraged to use such areas as natural conservation areas and, potentially, to reforest them if they do not have forest cover.

10-A.1.1 Basis for Determining the Recharge Volume

- If more than one HSG is present at a site, a composite soil-specific recharge factor should be computed based on the proportion of total site area within each HSG. The recharge volume provided at the site should be directed toward the most permeable HSG available or toward an infiltration-type BMP, preferably incorporating amended soil or filtration media.

- The "percent volume" method is typically used to determine the Re_v requirement when structural practices are used to provide recharge. These practices must be able to provide seepage into the ground and may include infiltration and exfiltration structures (e.g., infiltration, bioretention, dry swales or sand filters with storage below the underdrain). Structures that require impermeable liners, intercept groundwater, or are designed for trapping sediment (e.g., forebays) should not be used for this purpose. In this method, the volume of runoff directed to the structural practices should meet or exceed the computed recharge volume.

- The "percent area" method is typically used to determine the Re_v requirement when non-structural practices are used. Under this method, the recharge requirement is evaluated by mapping the percent of impervious area that is effectively served by an acceptable non-structural practice and comparing it to the minimum recharge requirement. Acceptable non-structural practices include filter strips that treat rooftop or parking lot runoff, sheet flow discharge to stream buffers, and grass channels that treat roadway runoff.

- The recharge volume criteria should not apply to any portion of a site that is designated as a stormwater hotspot nor any project considered as redevelopment. In addition, the appropriate local review authority may alter or eliminate the recharge volume requirement if the site is situated on unsuitable soils (e.g., marine clays) or in an urban redevelopment area. In this situation, non-structural practices (percent area method) should be implemented and any remaining or untreated Re_v should be included in the treatment volume (T_v).

- If Re_V is treated by structural or non-structural practices separate and upstream of the T_V treatment, the T_V should be adjusted accordingly.

NOTE: The Re_v and the T_v are inclusive. Therefore, if a local government does choose to establish separate Groundwater Recharge criteria, the Re_v may be subtracted from the T_v when sizing the water quality BMP.

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Appendix 10-B

Better Protection from Stream Channel Erosion

Studies now show that, depending on the setting, natural channels are shaped by rainfall events ranging from the 0.9-year storm to the 1.8-year frequency storm event. In suburban and rural settings, the channel forming storm is more likely to be near the high end of this range (1.5-year to 1.8-year storm). This storm frequency allows the channel to maintain a state of equilibrium with regard to natural sediment load transport and natural vegetation, which helps to stabilize channel banks.

Note, however, that a peak discharge rollback requirement does not address the increase in the *frequency* of that peak runoff rate. Urbanization usually increases the amount of impervious cover, resulting in less infiltration, less initial abstraction and less depression storage. Consequently, it takes less rainfall to produce the same *volume* of runoff. Therefore, the *peak rate of runoff* that normally occurs with a 2-year frequency storm before development, may occur several times a year following development.

To compound the problem, a detention basin stores the increased *volume* of runoff from a developed area and releases it at the pre-development rate. The *duration* of this discharge is much longer than the pre-development condition, keeping the soils of the bank saturated for a longer time. The peak rate and velocity may be at pre-development levels, but by receiving the pre-development rate for a longer *duration*, coupled with the increase in *frequency*, a stable earth-lined channel can quickly degrade. And, in fact, this is what has been happening to stream channels receiving runoff from most development sites.

The increased frequency of a specific discharge can be illustrated by considering an undeveloped watershed which, during a two-year frequency storm (3.2 inches of rain in Virginia), generates a theoretical peak rate of runoff of 15 cubic feet per second (cfs), and a corresponding volume of runoff of 0.52 watershed inches. We will assume that this two-year frequency flow represents the channel forming, bankfull discharge. After the watershed has experienced development (32% imperviousness) along with the associated improved drainage conveyance systems, the same watershed requires only 1.6 inches of rainfall to generate that same theoretical bankfull discharge of 15 cfs. This means that the channel will now experience bankfull flows at an approximate increased *frequency* of every three to six months rather than once every two years. In addition, for the 2-year storm, the *volume* of runoff has increased to 1.15 watershed inches, more than double the pre-development runoff volume, which means a significant increase in the *duration* of the peak flow can be expected. Under this scenario, the receiving stream will experience a significant increase in erosive flows.

Designs that effectively prevent stream channel erosion evolve from the study of stream channel geomorphology. Several studies have indicated that the level of erosion (or bed-material load) is a function of the difference between the flow velocity and the *critical* velocity.(McCuen, 1987). The critical velocity is a function of the type of soil of which the channel bed is composed. The studies indicate that the amount of bed sediment moved is a function of the duration of time during which the velocity is greater than the critical velocity. According to McCuen, this explains from a conceptual standpoint why the duration of flow is just as important as the rate of flow. Further, it may explain why detention basins may actually increase the erosion compared to providing no control of the post-developed flows. When no control is provided, the flow tends to exceed the channel capacity and extend out into the floodplain; thus the velocity within the channel banks may not increase significantly even though the peak flow rate does increase significantly.

This should not be interpreted as justification for no control of stormwater runoff. Rather, it highlights the need for design criteria that replicate the pre-development sediment load transport characteristics of the channel. Several methodologies have been recommended, some of which are very subjective as they are based upon the ability of the designer to analyze and interpret the stream sediment and shear stress characteristics. This could easily become an expensive and cumbersome methodology, especially in localities that do not experience significant development pressure. The review and approval process could become bogged down in the analysis of field data and trying to verify the channel characteristics, especially when the requirements of the field work may be different for every project.